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Search for a standard model-like Higgs boson in the $\mu^+\mu^-$ and e^+e^- decay channels at the LHC

CMS Collaboration*

CERN, Switzerland



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ABSTRACT

A search is presented for a standard model-like Higgs boson decaying to the $\mu^+\mu^-$ or e^+e^- final states based on proton–proton collisions recorded by the CMS experiment at the CERN LHC. The data correspond to integrated luminosities of 5.0 fb^{-1} at a centre-of-mass energy of 7 TeV and 19.7 fb^{-1} at 8 TeV for the $\mu^+\mu^-$ search, and of 19.7 fb^{-1} at 8 TeV for the e^+e^- search. Upper limits on the production cross section times branching fraction at the 95% confidence level are reported for Higgs boson masses in the range from 120 to 150 GeV. For a Higgs boson with a mass of 125 GeV decaying to $\mu^+\mu^-$, the observed (expected) upper limit on the production rate is found to be 7.4 ($6.5^{+2.8}_{-1.9}$) times the standard model value. This corresponds to an upper limit on the branching fraction of 0.0016. Similarly, for e^+e^- , an upper limit of 0.0019 is placed on the branching fraction, which is $\approx 3.7 \times 10^5$ times the standard model value. These results, together with recent evidence of the 125 GeV boson coupling to τ -leptons with a larger branching fraction consistent with the standard model, confirm that the leptonic couplings of the new boson are not flavour-universal.

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1. Introduction

After the discovery of a particle with a mass near 125 GeV [1–3] and properties in agreement, within current experimental uncertainties, with those expected of the standard model (SM) Higgs boson, the next critical question is to understand in greater detail the nature of the newly discovered particle. Answering this question with a reasonable confidence requires measurements of its properties and production rates into final states both allowed and disallowed by the SM. Beyond the standard model (BSM) scenarios may contain additional Higgs bosons, so searches for these additional states constitute another test of the SM [4]. For a Higgs boson mass, m_H , of 125 GeV, the SM prediction for the Higgs to $\mu^+\mu^-$ branching fraction, $\mathcal{B}(H \rightarrow \mu^+\mu^-)$, is among the smallest accessible at the CERN LHC, 2.2×10^{-4} [5], while the SM prediction for $\mathcal{B}(H \rightarrow e^+e^-)$ of approximately 5×10^{-9} is inaccessible at the LHC. Experimentally, however, $H \rightarrow \mu^+\mu^-$ and $H \rightarrow e^+e^-$ are the cleanest of the fermionic decays. The clean final states allow a better sensitivity, in terms of cross section, σ , times branching fraction, \mathcal{B} , than $H \rightarrow \tau^+\tau^-$. This means that

searches for $H \rightarrow \mu^+\mu^-$ and $H \rightarrow e^+e^-$, combined with recent strong evidence for decays of the new boson to $\tau^+\tau^-$ [6,7], may be used to test if the coupling of the new boson to leptons is flavour-universal or proportional to the lepton mass, as predicted by the SM [8]. In addition, a measurement of the $H \rightarrow \mu^+\mu^-$ decay probes the Yukawa coupling of the Higgs boson to second-generation fermions, an important input in understanding the mechanism of electroweak symmetry breaking in the SM [9,10]. Deviations from the SM expectation could also be a sign of BSM physics [11,12]. A previous LHC search for SM $H \rightarrow \mu^+\mu^-$ has been performed by the ATLAS Collaboration and placed a 95% confidence level (CL) upper limit of 7.0 times the rate expected from the SM at 125.5 GeV [13]. The ATLAS Collaboration has also performed a search for BSM $H \rightarrow \mu^+\mu^-$ decays within the context of the minimal supersymmetric standard model [14].

This paper reports a search for an SM-like Higgs boson decaying to either a pair of muons or electrons ($H \rightarrow \ell^+\ell^-$) in proton–proton collisions recorded by the CMS experiment at the LHC. The $H \rightarrow \mu^+\mu^-$ search is performed on data corresponding to integrated luminosities of $5.0 \pm 0.1 \text{ fb}^{-1}$ at a centre-of-mass energy of 7 TeV and $19.7 \pm 0.5 \text{ fb}^{-1}$ at 8 TeV, while the $H \rightarrow e^+e^-$ search is only performed on the 8 TeV data. Results are presented for Higgs boson masses between 120 and 150 GeV. For $m_H = 125 \text{ GeV}$,

* E-mail address: cms-publication-committee-chair@cern.ch.

the SM predicts 19(95) $H \rightarrow \mu^+ \mu^-$ events at 7 TeV (8 TeV), and $\approx 2 \times 10^{-3}$ $H \rightarrow e^+ e^-$ events at 8 TeV [15–18].

The $H \rightarrow \ell^+ \ell^-$ resonance is sought as a peak in the dilepton mass spectrum, $m_{\ell\ell}$, on top of a smoothly falling background dominated by contributions from Drell–Yan production, $t\bar{t}$ production, and vector boson pair-production processes. Signal acceptance and selection efficiency are estimated using Monte Carlo (MC) simulations, while the background is estimated by fitting the observed $m_{\ell\ell}$ spectrum in data, assuming a smooth functional form.

Near $m_H = 125$ GeV, the SM predicts a Higgs boson decay width much narrower than the dilepton invariant mass resolution of the CMS experiment. For $m_H = 125$ GeV, the SM predicts the Higgs boson decay width to be 4.2 MeV [16], and experimental results indirectly constrain the width to be < 22 MeV at the 95% CL, subject to various assumptions [19,20]. The experimental resolution depends on the angle of each reconstructed lepton relative to the beam axis. For dimuons, the full width at half maximum (FWHM) of the signal peak ranges from 3.9 to 6.2 GeV (for muons with $|\eta| < 2.1$), while for electrons it ranges from 4.0 to 7.2 GeV (for electrons with $|\eta| < 1.44$ or $1.57 < |\eta| < 2.5$).

The sensitivity of this analysis is increased through an extensive categorization of the events, using kinematic variables to isolate regions with a large signal over background (S/B) ratio from regions with smaller S/B ratios. Separate categories are optimized for the dominant Higgs boson production mode, gluon-fusion (GF), and the sub-dominant production mode, vector boson fusion (VBF). Higgs boson production in association with a vector boson (VH), while not optimized for, is taken into account in the $H \rightarrow \mu^+ \mu^-$ analysis. The SM predicts Higgs boson production to be 87.2% GF, 7.1% VBF, and 5.1% VH for $m_H = 125$ GeV at 8 TeV [18]. In addition to $m_{\ell\ell}$, the most powerful variables for discriminating between the Higgs boson signal and the Drell–Yan and $t\bar{t}$ backgrounds are the jet multiplicity, the dilepton transverse-momentum ($p_T^{\ell\ell}$), and the invariant mass of the two largest transverse-momentum jets (m_{jj}). The gluon–gluon initial state of GF production tends to lead to more jet radiation than the quark–antiquark initial state of Drell–Yan production, leading to larger $p_T^{\ell\ell}$ and jet multiplicity. Similarly, VBF production involves a pair of forward–backward jets with a large m_{jj} compared to Drell–Yan plus two-jet or $t\bar{t}$ production. Events are further categorized by their $m_{\ell\ell}$ resolution and the kinematics of the jets and leptons.

This paper is organized as follows. Section 2 introduces the CMS detector and event reconstruction, Section 3 describes the $H \rightarrow \mu^+ \mu^-$ event selection, Section 4 the $H \rightarrow \mu^+ \mu^-$ selection efficiency, Section 5 details the systematic uncertainties included in the $H \rightarrow \mu^+ \mu^-$ analysis, Section 6 presents the results of the $H \rightarrow \mu^+ \mu^-$ search, Section 7 describes the $H \rightarrow e^+ e^-$ search, and Section 8 provides a summary.

2. CMS detector and event reconstruction

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass/scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors.

The first level of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4 μ s. The high level trig-

ger processor farm further decreases the event rate from at most 100 kHz to less than 1 kHz, before data storage. A more detailed description of the detector as well as the definition of the coordinate system and relevant kinematic variables can be found in Ref. [21].

The CMS offline event reconstruction creates a global event description by combining information from all subdetectors. This combined information then leads to a list of particle-flow (PF) objects [22,23]: candidate muons, electrons, photons, and hadrons. By combining information from all subdetectors, particle identification and energy estimation performance are improved. In addition, double counting subdetector energy deposits when reconstructing different particle types is eliminated.

Due to the high instantaneous luminosity of the LHC, many proton–proton interactions occur in each bunch crossing. An average of 9 and 21 interactions occur in each bunch crossing for the 7 and 8 TeV data samples, respectively. Most interactions produce particles with relatively low transverse-momentum (p_T), compared to the particles produced in an $H \rightarrow \ell^+ \ell^-$ signal event. These interactions are termed “pileup”, and can interfere with the reconstruction of the high- p_T interaction, whose vertex is identified as the vertex with the largest scalar sum of the squared transverse momenta of the tracks associated with it. All charged PF objects with tracks coming from another vertex are then removed.

Hadronic jets are clustered from reconstructed PF objects with the infrared- and collinear-safe anti- k_T algorithm [24,25], operated with a size parameter of 0.5. The jet momentum is determined as the vectorial sum of the momenta of all PF objects in the jet, and is found in the simulation to be within 5% to 10% of the true momentum over the whole p_T spectrum of interest and detector acceptance. An offset correction is applied to take into account the extra neutral energy clustered in jets due to pileup. Jet energy corrections are derived from the simulation, and are confirmed by in-situ measurements of the energy balance in di-jet, photon plus jet, and Z plus jet (where the Z-boson decays to $\mu^+ \mu^-$ or $e^+ e^-$) events [26]. The jet energy resolution is 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV [27]. Additional selection criteria are applied to each event to remove spurious jet-like objects originating from isolated noise patterns in certain HCAL regions.

Matching muons to tracks measured in the silicon tracker results in a relative p_T resolution for muons with $20 < p_T < 100$ GeV of 1.3–2.0% in the barrel and better than 6% in the endcaps. The p_T resolution in the barrel is better than 10% for muons with p_T up to 1 TeV [28]. The mass resolution for $Z \rightarrow \mu\mu$ decays is between 1.1% and 1.9% depending on the pseudorapidity of each muon, for $|\eta| < 2.1$. The mass resolution for $Z \rightarrow ee$ decays when both electrons are in the ECAL barrel (endcaps) is 1.6% (2.6%) [29].

3. $H \rightarrow \mu^+ \mu^-$ event selection

Online collection of events is performed with a trigger that requires at least one isolated muon candidate with p_T above 24 GeV in the pseudorapidity range $|\eta| \leq 2.1$. In the offline selection, muon candidates are required to pass the “Tight muon selection” [28] and each muon trajectory is required to have an impact parameter with respect to the primary vertex smaller than 5 mm and 2 mm in the longitudinal and transverse directions, respectively. They must also have $p_T > 15$ GeV and $|\eta| \leq 2.1$.

For each muon candidate, an isolation variable is constructed using the scalar sum of the transverse-momentum of particles, reconstructed as PF objects, within a cone centered on the muon. The boundary of the cone is $\Delta R = \sqrt{[b](\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ away from the muon, and the p_T of the muon is not included in the sum. While only charged particles associated with the primary vertex

are taken into account, a correction must be applied for contamination from neutral particles coming from pileup interactions. On average, in inelastic proton–proton collisions, neutral pileup particles deposit half as much energy as charged pileup particles. The amount of energy coming from charged pileup particles is estimated as the sum of the transverse momenta of charged tracks originating from vertices other than the primary vertex, but still entering the isolation cone. The neutral pileup energy in the isolation cone is then estimated to be 50% of this value and subtracted from the muon isolation variable. A muon candidate is accepted if the corrected isolation variable is less than 12% of the muon p_T .

To pass the offline selection, events must contain a pair of opposite-sign muon candidates passing the above selection, and the muon which triggered the event is required to have $p_T > 25$ GeV. All combinations of opposite-sign pairs, where one of the muons triggers the event, are considered as dimuon candidates in the dimuon invariant mass distribution analysis. Each pair is effectively treated as a separate event, and referred to as such for the remainder of this paper. Less than 0.1% of the SM Higgs boson events and 0.005% of the background events in each category contain more than one pair of muons.

After selecting events with a pair of isolated opposite-sign muons, events are categorized according to the properties of jets. Jets reconstructed from PF objects are only considered if their p_T is greater than 30 GeV and $|\eta| < 4.7$. A multivariate analysis (MVA) technique is used to discriminate between jets originating from hard interactions and jets originating from pileup [30].

Dimuon events are classified into two general categories: a 2-jet category and a 0, 1-jet category. The 2-jet category requires at least two jets, with $p_T > 40$ GeV for the leading jet and $p_T > 30$ GeV for the subleading jet. A 2-jet event must also have $p_T^{\text{miss}} < 40$ GeV, where p_T^{miss} is the magnitude of the vector sum of the transverse momenta of the dimuon and dijet systems. The p_T^{miss} requirement reduces the $t\bar{t}$ contamination in the 2-jet category, since $t\bar{t}$ decays also include missing transverse momentum due to neutrinos. All dimuon events not selected for the 2-jet category are placed into the 0, 1-jet category where the signal is produced dominantly by GF.

The 2-jet category is further divided into VBF Tight, GF Tight, and Loose subcategories. The VBF Tight category has a large S/B ratio for VBF produced events. It requires $m_{jj} > 650$ GeV and $|\Delta\eta(jj)| > 3.5$, where $|\Delta\eta(jj)|$ is the absolute value of the difference in pseudorapidity between the two leading jets. For an SM Higgs boson with $m_H = 125$ GeV, 79% of the signal events in this category are from VBF production. Signal events in the 2-jet category that do not pass the VBF Tight criteria mainly arise from GF events, which contain two jets from initial-state radiation. The GF Tight category captures these events by requiring the dimuon transverse momentum ($p_T^{\mu\mu}$) to be greater than 50 GeV and $m_{jj} > 250$ GeV. To further increase the sensitivity of this search, 2-jet events that fail the VBF Tight and GF Tight criteria are still retained in a third subcategory called 2-jet Loose.

In the 0, 1-jet category, events are split into two subcategories based on the value of $p_T^{\mu\mu}$. The most sensitive subcategory is 0, 1-jet Tight which requires $p_T^{\mu\mu}$ greater than 10 GeV, while the events with $p_T^{\mu\mu}$ less than 10 GeV are placed in the 0, 1-jet Loose subcategory. The S/B ratio is further improved by categorizing events based on the dimuon invariant mass resolution as follows. Given the narrow Higgs boson decay width, the mass resolution fully determines the shape of the signal peak. The dimuon mass resolution is dominated by the muon p_T resolution, which worsens with increasing $|\eta|$ [28]. Hence, events are further sorted into subcategories based on the $|\eta|$ of each muon and are labeled as “barrel” muons (B) for $|\eta| < 0.8$, “overlap” muons (O) for

$0.8 \leq |\eta| < 1.6$, and “endcap” muons (E) for $1.6 \leq |\eta| < 2.1$. The 0, 1-jet dimuon events are then assigned, within the corresponding Tight and Loose categories, to all possible dimuon $|\eta|$ combinations. The dimuon mass resolution for each category is shown in Table 1. Due to the limited size of the data samples, the 2-jet subcategories are not split into further subcategories according to the muon p_T resolution. This leads to a total of fifteen subcategories: three 2-jet subcategories, six 0, 1-jet Tight subcategories, and six 0, 1-jet Loose subcategories.

4. $H \rightarrow \mu^+ \mu^-$ event selection efficiency

While the background shape and normalization are obtained from data, the selection efficiency for signal events has to be determined using MC simulation. For the GF and VBF production modes, signal samples are produced using the POWHEG-box next-to-leading-order (NLO) generator [31–33] interfaced with PYTHIA 6.4.26 [34] for parton showering. VH samples are produced using HERWIG++ [35] and its integrated implementation of the NLO POWHEG method.

These samples are then passed through a simulation of the CMS detector, based on GEANT4 [36], that has been extensively validated on both 7 and 8 TeV data. This validation includes a comparison of data with MC simulations of the Drell–Yan plus jets and $t\bar{t}$ plus jets backgrounds produced using MADGRAPH [37] interfaced with PYTHIA 6.4.26 for parton showering. In all categories, the simulated $m_{\mu\mu}$ spectra agree well with the data, for $110 < m_{\mu\mu} < 160$ GeV. Scale factors related to muon identification, isolation, and trigger efficiency are applied to each simulated signal sample to correct for discrepancies between the detector simulation and data. These scale factors are estimated using the “tag-and-probe” technique [28]. The detector simulation and data typically agree to within 1% on the muon identification efficiency, to within 2% on the muon isolation efficiency, and to within 5% on the muon trigger efficiency.

The overall acceptance times selection efficiency for the $H \rightarrow \mu^+ \mu^-$ signal depends on the mass of the Higgs boson. For a Higgs boson mass of 125 GeV, the acceptance times selection efficiencies are shown in Table 1.

5. $H \rightarrow \mu^+ \mu^-$ systematic uncertainties

Since the statistical analysis is performed on the dimuon invariant mass spectrum, it is necessary to categorize the sources of systematic uncertainties into “shape” uncertainties that change the shape of the dimuon invariant mass distribution, and “rate” uncertainties that affect the overall signal yield in each category.

The only relevant shape uncertainties for the signal are related to the knowledge of the muon momentum scale and resolution and they affect the width of the signal peak by 3%. The signal shape is parameterized by a double-Gaussian (see Section 6) and this uncertainty is applied by constraining the width of the narrower Gaussian. The probability density function used to constrain this nuisance parameter in the limit setting procedure is itself a Gaussian with its mean set to the nominal value and its width set to 3% of the nominal value.

Rate uncertainties in the signal yield are evaluated separately for each Higgs boson production process and each centre-of-mass energy. These uncertainties are applied using log-normal probability density functions as described in Ref. [38]. Table 2 shows the relative systematic uncertainties in the signal yield for $m_H = 125$ GeV, with more detail given below.

To estimate the theoretical uncertainty in the signal production processes due to neglected higher-order quantum corrections, the renormalization and factorization scales are varied simultaneously

Table 1

Details regarding each of the $H \rightarrow \mu^+ \mu^-$ categories. The top half of the table refers to the $5.0 \pm 0.1 \text{ fb}^{-1}$ at 7 TeV, while the bottom half refers to the $19.7 \pm 0.5 \text{ fb}^{-1}$ at 8 TeV. Each row lists the category name, FWHM of the signal peak, acceptance times selection efficiency ($A\epsilon$) for GF, $A\epsilon$ for VBF, $A\epsilon$ for VH, expected number of SM signal events in the category for $m_H = 125 \text{ GeV}$ (N_S), number of background events within an FWHM-wide window centered on 125 GeV estimated by a signal plus background fit to the data (N_B), number of observed events within an FWHM-wide window centered on 125 GeV (N_{Data}), systematic uncertainty to account for the parameterization of the background (N_P), and N_P divided by the statistical uncertainty on the fitted number of signal events (N_P/σ_{Stat}). The expected number of SM signal events is $N_S = \mathcal{L} \times (\sigma B A\epsilon)_{\text{GF}} + \mathcal{L} \times (\sigma B A\epsilon)_{\text{VBF}} + \mathcal{L} \times (\sigma B A\epsilon)_{\text{VH}}$, where \mathcal{L} is the integrated luminosity and σB is the SM cross section times branching fraction.

Category	FWHM [GeV]	$A\epsilon$ [%]			N_S	N_B	N_{Data}	N_P	N_P/σ_{Stat} [%]
		GF	VBF	VH					
0, 1-jet Tight BB	3.4	9.7	8.1	8.9	1.83	226.4	245	22.5	101
0, 1-jet Tight BO	4.0	14.0	11.0	13.0	2.56	470.3	459	42.4	121
0, 1-jet Tight BE	4.4	4.9	3.8	4.8	0.92	234.8	235	16.6	65
0, 1-jet Tight OO	4.8	5.2	3.9	4.9	0.97	226.5	236	11.5	52
0, 1-jet Tight OE	5.3	4.0	3.0	4.2	0.75	237.5	228	26.5	106
0, 1-jet Tight EE	5.9	0.9	0.7	1.0	0.17	71.4	57	11.4	97
0, 1-jet Loose BB	3.2	2.2	0.1	0.1	0.38	151.4	127	17.2	95
0, 1-jet Loose BO	3.9	3.1	0.2	0.2	0.52	307.0	291	18.9	71
0, 1-jet Loose BE	4.2	1.2	0.1	0.1	0.20	148.7	178	19.1	102
0, 1-jet Loose OO	4.5	1.2	0.1	0.1	0.20	144.7	143	19.1	113
0, 1-jet Loose OE	5.1	1.0	0.1	0.1	0.16	160.1	159	16.1	75
0, 1-jet Loose EE	5.8	0.2	0.0	0.0	0.03	41.6	39	5.6	51
2-jet VBF Tight	4.4	0.1	8.7	0.0	0.14	1.3	2	0.5	24
2-jet GF Tight	4.5	0.5	7.9	0.5	0.20	12.9	16	1.7	27
2-jet Loose	4.3	2.1	6.2	10.2	0.53	66.2	78	8.4	64
Sum of categories	–	50.3	53.9	48.1	9.56	2500.8	2493	–	–
0, 1-jet Tight BB	3.9	9.6	7.1	8.5	8.87	1208.0	1311	40.8	73
0, 1-jet Tight BO	4.4	13.0	10.0	13.0	12.45	2425.3	2474	102.2	127
0, 1-jet Tight BE	4.7	4.9	3.4	4.6	4.53	1204.8	1212	63.8	111
0, 1-jet Tight OO	5.0	5.3	3.6	5.0	4.90	1112.7	1108	39.0	71
0, 1-jet Tight OE	5.5	4.1	2.8	4.2	3.85	1162.1	1201	151.1	251
0, 1-jet Tight EE	6.4	0.9	0.6	1.1	0.85	350.8	323	34.2	107
0, 1-jet Loose BB	3.7	2.1	0.1	0.1	1.73	715.4	697	40.2	94
0, 1-jet Loose BO	4.3	2.9	0.2	0.2	2.41	1436.4	1432	85.5	158
0, 1-jet Loose BE	4.5	1.1	0.1	0.1	0.90	725.9	782	74.9	166
0, 1-jet Loose OO	4.9	1.1	0.1	0.1	0.96	727.4	686	33.2	74
0, 1-jet Loose OE	5.5	0.9	0.1	0.1	0.76	791.8	832	78.2	158
0, 1-jet Loose EE	6.2	0.2	0.0	0.0	0.18	218.5	209	18.9	87
2-jet VBF Tight	5.0	0.2	11.0	0.0	0.95	10.6	8	1.6	35
2-jet GF Tight	5.1	0.7	8.4	0.6	1.14	74.8	76	11.8	88
2-jet Loose	4.7	2.4	6.3	10.4	2.90	431.7	387	25.3	73
Sum of categories	–	49.4	53.8	48.0	47.38	12596.2	12738	–	–

Table 2

The relative systematic uncertainty in the $H \rightarrow \mu^+ \mu^-$ signal yield is listed for each uncertainty source. Uncertainties are shown for the GF and VBF Higgs boson production modes. The systematic uncertainties vary depending on the category and centre-of-mass energy.

Source	GF [%]	VBF [%]
Higher-order corrections [18]	1–25	1–7
PDF [18]	11	5
PS/UE	6–60	2–15
$\mathcal{B}(H \rightarrow \mu^+ \mu^-)$ [18]	6	6
Integrated luminosity [39,40]	2.2–2.6	2.2–2.6
MC statistics	1–8	1–8
Muon efficiency	1.6	1.6
Pileup	<1–5	<1–2
Jet energy resolution	1–3	1–2
Jet energy scale	1–8	2–6
Pileup jet rejection	1–4	1–4

by a factor of two up and down from their nominal values. This leads to an uncertainty in the cross section and acceptance times efficiency which depends on the mass of the Higgs boson. The uncertainty is largest in the 2-jet VBF Tight and GF Tight categories, and smallest in the 0, 1-jet Tight categories.

Uncertainty in the knowledge of the parton distribution functions (PDFs) also leads to uncertainty in the signal production process. This uncertainty is estimated using the PDF4LHC prescription [41,42] and the CT10 [43], MSTW2008 [44], and NNPDF 2.3 [45] PDF sets provided by the LHAPDF package version 5.8.9 [46]. The value of the uncertainty depends on the mass

of the Higgs boson, while the dependence on the category is small.

Uncertainty in the modeling of the parton showers and underlying event activity (PS/UE) may affect the kinematics of selected jets. This uncertainty is estimated by comparing various tunes of the relevant PYTHIA parameters. The D6T [47], PO [48], ProPT0, and ProQ20 [49] tunes are compared with the Z2* [47] tune, which is the nominal choice. The uncertainty is larger in the 2-jet categories than in the 0, 1-jet categories. Large uncertainties in the 2-jet categories are expected for the GF production mode, since two-jet events are simulated solely by parton showering in the POWHEG–PYTHIA NLO samples.

Misidentification of “hard jets” (jets originating from the hard interaction) as “pileup jets” (jets originating from pileup interactions) can lead to migration of signal events from the 2-jet category to the 0, 1-jet category. Events containing a Z-boson, tagged by its dilepton decay, recoiling against a jet provide a pure source of hard jets similar to the Higgs boson signal. Data events may then be used to estimate the misidentification rate of the MVA technique used to discriminate between hard jets and pileup jets using data [30]. A pure source of hard jets is found by selecting events with $p_T^Z > 30 \text{ GeV}$ and jets where $|\Delta\phi(Z, j)| > 2.5$ and $0.5 < p_T^j/p_T^Z < 1.5$. The misidentification rate of these jets as pileup jets is compared in data and simulation, and the difference taken as a systematic uncertainty.

There are several additional uncertainties. The theoretical uncertainty in the branching fraction to $\mu^+ \mu^-$ is taken from Ref. [18], and depends on the Higgs boson mass. The uncertainty

in the luminosity is directly applied to the signal yield in all categories. The signal yield uncertainty due to the limited size of the simulated event samples depends on the category, and is listed as “MC statistics” in Table 2. There is a small uncertainty associated with the “tag-and-probe” technique used to determine the data to simulation muon efficiency scale factors [28]. This uncertainty is labeled “Muon efficiency” in Table 2. A systematic uncertainty in the knowledge of the pileup multiplicity is evaluated by varying the total cross section for inelastic proton–proton collisions. The acceptance and selection efficiency of the jet-based selections are affected by uncertainty in the jet energy resolution and absolute jet energy scale calibration [26].

For VH production, only rate uncertainties in the production cross section due to quantum corrections and PDFs are considered. They are 3% or less [18].

When estimating each of the signal yield uncertainties, attention is paid to the sign of the yield variation in each category. Categories that vary in the same direction are considered fully correlated while categories that vary in opposite directions are considered anticorrelated. These correlations are considered between all categories at both beam energies for all of the signal yield uncertainties except for the luminosity uncertainty and the uncertainty caused by the limited size of the simulated event samples. The luminosity uncertainty is considered fully correlated between all categories, but uncorrelated between the two centre-of-mass energies. The MC simulation statistical uncertainty is considered uncorrelated between all categories and both centre-of-mass energies.

To account for the possibility that the nominal background parameterization may imperfectly describe the true background shape, an additional systematic uncertainty is included. This uncertainty is implemented as a floating additive contribution to the number of signal events, constrained by a Gaussian probability density function with mean set to zero and width set to the systematic uncertainty. This systematic uncertainty is estimated by checking the bias in terms of the number of signal events that are found when fitting the signal plus nominal background model (see Section 6) to pseudo-data generated from various alternative background models, including polynomials, that were fit to data. Bias estimates are performed for Higgs boson mass points from 120 to 150 GeV. The uncertainty estimate is then taken as the maximum absolute value of the bias of all of the mass points and all of the alternative background models. It is then applied uniformly to all Higgs boson masses. The estimates of the uncertainty in the parameterization of the background (N_p) are shown in Table 1 for each category. The effect of this systematic uncertainty is larger than all of the others. The expected limit (see Section 6) would be 20% lower at $m_H = 125$ GeV without the systematic uncertainty in the parameterization of the background.

6. $H \rightarrow \mu^+ \mu^-$ results

To estimate the signal rate, the dimuon invariant mass ($m_{\mu\mu}$) spectrum is fit with the sum of parameterized signal and background shapes. This fit is performed simultaneously in all of the categories. Since in the mass range of interest the natural width of the Higgs boson is narrower than the detector resolution, the $m_{\mu\mu}$ shape is only dependent on the detector resolution and QED final state radiation. A double-Gaussian function is chosen to parameterize the shape of the signal. The parameters that specify the signal shape are estimated by fitting the double-Gaussian function to simulated signal samples. A separate set of signal shape parameters are used for each category. The background shape, dominated by the Drell–Yan process, is modeled by a function, $f(m_{\mu\mu})$, that is the sum of a Breit–Wigner function and a $1/m_{\mu\mu}^2$ term, to model

the Z-boson and photon contributions, both multiplied by an exponential function to approximate the effect of the PDF on the $m_{\mu\mu}$ distribution. This function is shown in the following equation, and involves the parameters λ , β , m_Z , and Γ :

$$f(m_{\mu\mu}) = \beta C_1 e^{-\lambda m_{\mu\mu}} \frac{1}{(m_{\mu\mu} - m_Z)^2 + \frac{\Gamma^2}{4}} + (1 - \beta) C_2 e^{-\lambda m_{\mu\mu}} \frac{1}{m_{\mu\mu}^2}. \quad (1)$$

The coefficients C_1 and C_2 are set to ensure the integral of each of the two terms is normalized to unity in the $m_{\mu\mu}$ fit range, 110 to 160 GeV. Each category uses a different set of background parameters. Before results are extracted, the mass and width of the Z-boson peak, m_Z and Γ , are estimated by fitting a Breit–Wigner function to the Z-boson mass peak region (88–94 GeV) in each category. The other parameters, λ and β , are fit simultaneously with the amount of signal in the signal plus background fit. Besides the Drell–Yan process, most of the remaining background events come from $t\bar{t}$ production. The background parameterization has been shown to fit the dimuon mass spectrum well, even when it includes a large $t\bar{t}$ fraction. Fits of the background model to data (assuming no signal contribution) are presented in Fig. 1 for the most sensitive categories: the 0, 1-jet Tight category with both muons reconstructed in the barrel region and the 2-jet VBF Tight category.

Results are presented in terms of the signal strength, which is the ratio of the observed (or expected) $\sigma\mathcal{B}$, to that predicted in the SM for the $H \rightarrow \mu^+ \mu^-$ process. Results are also presented, for $m_H = 125$ GeV, in terms of $\sigma\mathcal{B}$, and \mathcal{B} . No significant excess is observed. Upper limits at the 95% CL are presented using the CL_s criterion [50,51]. They are calculated using an asymptotic profile likelihood ratio method [38,52,53] involving dimuon mass shapes for each signal process and for background. Systematic uncertainties are incorporated as nuisance parameters and treated according to the frequentist paradigm [38].

Exclusion limits for Higgs boson masses from 120 to 150 GeV are shown in Fig. 2. The observed 95% CL upper limits on the signal strength at 125 GeV are 22.4 using the 7 TeV data and 7.0 using the 8 TeV data. The corresponding background-only expected limits are $16.6^{+7.3}_{-4.9}$ using the 7 TeV data and $7.2^{+3.2}_{-2.1}$ using the 8 TeV data. Accordingly, the combined observed limit for 7 and 8 TeV is 7.4, while the background-only expected limit is $6.5^{+2.8}_{-1.9}$. This corresponds to an observed upper limit on $\mathcal{B}(H \rightarrow \mu^+ \mu^-)$ of 0.0016, assuming the SM cross section. The best fit value of the signal strength for a Higgs boson mass of 125 GeV is $0.8^{+3.5}_{-3.4}$. We did not restrict the fit to positive values, to preserve the generality of the result.

Exclusion limits in terms of $\sigma(8 \text{ TeV})\mathcal{B}$ using only 8 TeV data are shown in Fig. 3 (top). The relative contributions of GF, VBF, and VH are assumed to be as predicted in the SM, and theoretical uncertainties on the cross sections and branching fractions are omitted. At 125 GeV, the observed 95% CL upper limit on $\sigma(7 \text{ TeV})\mathcal{B}$ using only 7 TeV data is 0.084 pb, while the background-only expected limit is $0.062^{+0.026}_{-0.018}$ pb. Using only 8 TeV data, the observed limit on $\sigma(8 \text{ TeV})\mathcal{B}$ is 0.033 pb, while the background-only expected limit is $0.034^{+0.014}_{-0.010}$ pb.

Exclusion limits on individual production modes may also be useful to constrain BSM models that predict $H \rightarrow \mu^+ \mu^-$ production dominated by a single mode. Limits are presented on the signal strength using a combination of 7 and 8 TeV data and on $\sigma(8 \text{ TeV})\mathcal{B}$ using only the 8 TeV data. The observed 95% CL upper limit on the GF signal strength, assuming the VBF and VH rates are zero, is 13.2, while the background-only expected limit

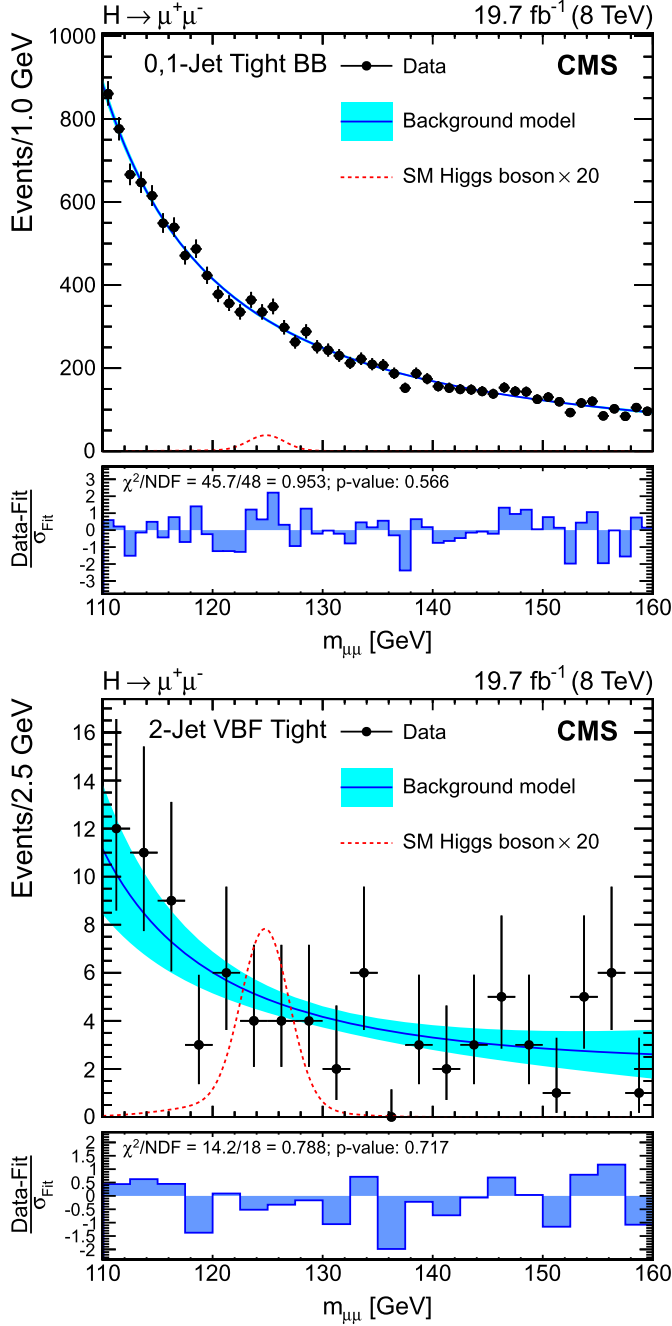


Fig. 1. The dimuon invariant mass at 8 TeV and the background model are shown for the 0, 1-jet Tight category when both muons are reconstructed in the barrel (top) and the 2-jet VBF Tight category (bottom). A best fit of the background model (see text) is shown by a solid line, while its fit uncertainty is represented by a lighter band. The dotted line illustrates the expected SM Higgs boson signal enhanced by a factor of 20, for $m_H = 125$ GeV. The lower histograms show the residual for each bin (Data-Fit) normalized by the Poisson statistical uncertainty of the background model (σ_{Fit}). Also given are the sum of squares of the normalized residuals (χ^2) divided by the number of degrees of freedom (NDF) and the corresponding p -value assuming the sum follows the χ^2 distribution.

is $9.8^{+4.4}_{-2.9}$. Similarly, the observed upper limit on the VBF signal strength, assuming the GF and VH rates are zero, is 11.2, while the background-only expected limit is $13.4^{+6.6}_{-4.2}$. The observed upper limit on $\sigma_{\text{GF}}(8 \text{ TeV})/\mathcal{B}$ is 0.056 pb and expected limit is $0.045^{+0.019}_{-0.013}$ pb, using only 8 TeV data. Similarly, the observed upper limit on $\sigma_{\text{VBF}}(8 \text{ TeV})/\mathcal{B}$ is 0.0036 pb and the expected limit is $0.0050^{+0.0024}_{-0.0015}$ pb, using only 8 TeV data.

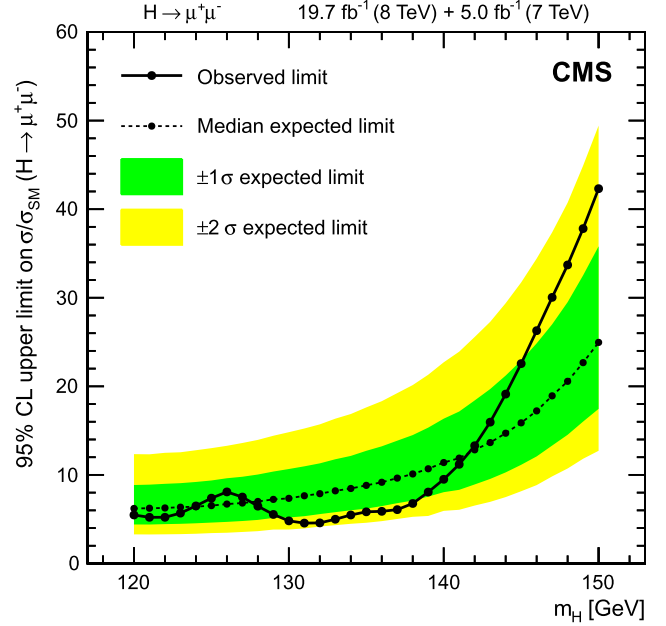


Fig. 2. Mass scan for the background-only expected and observed combined exclusion limits.

For $m_H = 125$ GeV, an alternative $H \rightarrow \mu^+\mu^-$ analysis was performed to check the results of the main analysis. It uses an alternative muon isolation variable based only on tracker information, an alternative jet reconstruction algorithm (the jet-plus-track algorithm [54]), and an alternative event categorization. The event categorization contains similar 2-jet categories to the main analysis, while separate categories are utilized for 0-jet and 1-jet events. Dimuon mass resolution-based categories are not used, but the 0-jet category does contain two subcategories separated by $p_T^{\mu\mu}$. As in the main analysis, results are extracted by fitting signal and background shapes to the $m_{\mu\mu}$ spectra in each category, but unlike the main analysis, $f(m_{\mu\mu}) = \exp(p_1 m_{\mu\mu}) / (m_{\mu\mu} - p_2)^2$ is used as the background shape. The systematic uncertainty on the parameterization of the background is estimated and applied in the same way as in the main analysis. For the alternative analysis, the observed (expected) 95% CL upper limit on the signal strength is 7.8 ($6.5^{+2.8}_{-1.9}$) for the combination of 7 TeV and 8 TeV data and $m_H = 125$ GeV. The observed limits of both the main and alternative analyses are within one standard deviation of their respective background-only expected limits, for $m_H = 125$ GeV.

7. Search for Higgs boson decays to e^+e^-

In the SM, the branching fraction of the Higgs boson into e^+e^- is tiny, because the fermionic decay width is proportional to the mass of the fermion squared. This leads to poor sensitivity to SM production for this search when compared to the search for $H \rightarrow \mu^+\mu^-$. On the other hand, the sensitivity in terms of $\sigma\mathcal{B}$ is similar to $H \rightarrow \mu^+\mu^-$, because dielectrons and dimuons share similar invariant mass resolutions, selection efficiencies, and backgrounds. Since the sensitivity to the SM rate of $H \rightarrow e^+e^-$ is so poor, an observation of the newly discovered particle decaying to e^+e^- with the current integrated luminosity would be evidence of physics beyond the standard model.

In a similar way to the $H \rightarrow \mu^+\mu^-$ analysis, a search in the m_{ee} spectrum is performed for a narrow peak over a smoothly falling background. The irreducible background is dominated by Drell-Yan production, with smaller contributions from $t\bar{t}$ and diboson pro-

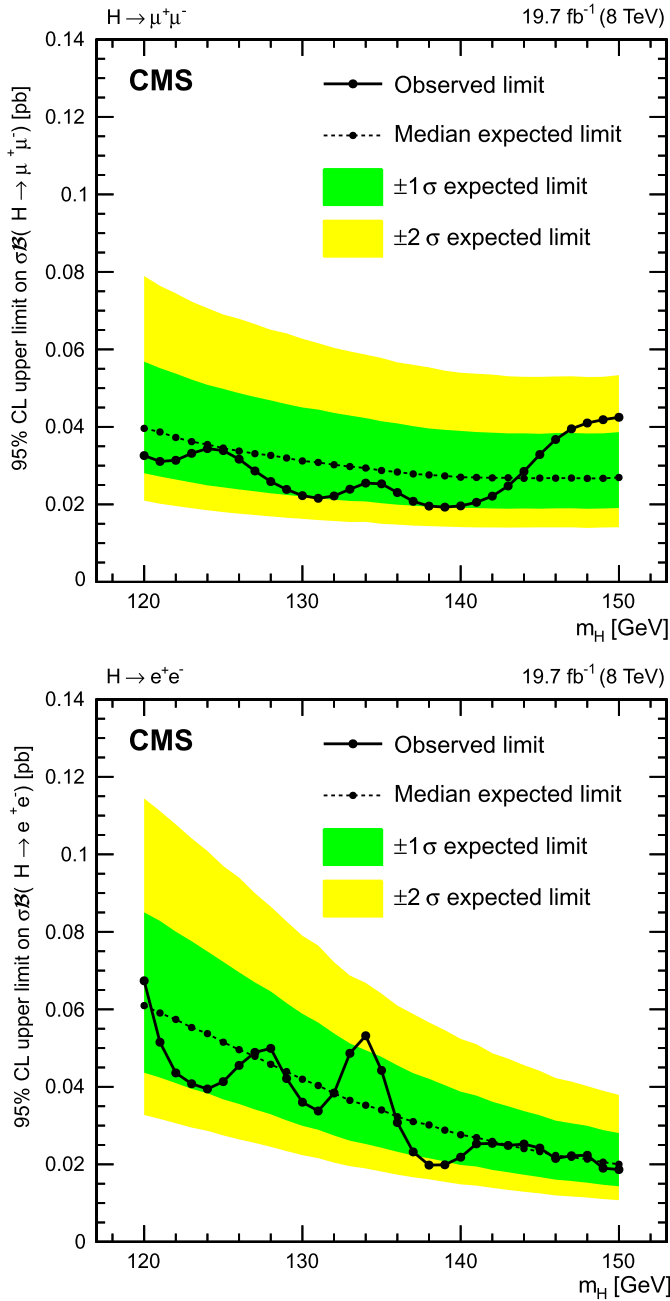


Fig. 3. Exclusion limits on $\sigma\mathcal{B}$ are shown for $H \rightarrow \mu^+\mu^-$ (top), and for $H \rightarrow e^+e^-$ (bottom), both for 8 TeV. Theoretical uncertainties on the cross sections and branching fraction are omitted, and the relative contributions of GF, VBF, and VH are as predicted in the SM.

Table 3

The relative systematic uncertainty in the $H \rightarrow e^+e^-$ signal yield is listed for each uncertainty source. Uncertainties are shown for the GF and VBF Higgs boson production modes. The systematic uncertainties vary depending on the category and centre-of-mass energy.

Source	GF [%]	VBF [%]
Higher-order corrections [18]	8–18	1–7
PDF [18]	11	5
PS/UE	6–42	3–10
Integrated luminosity [40]	2.6	2.6
Electron efficiency	2	2
Jet energy scale	<1–11	2–3

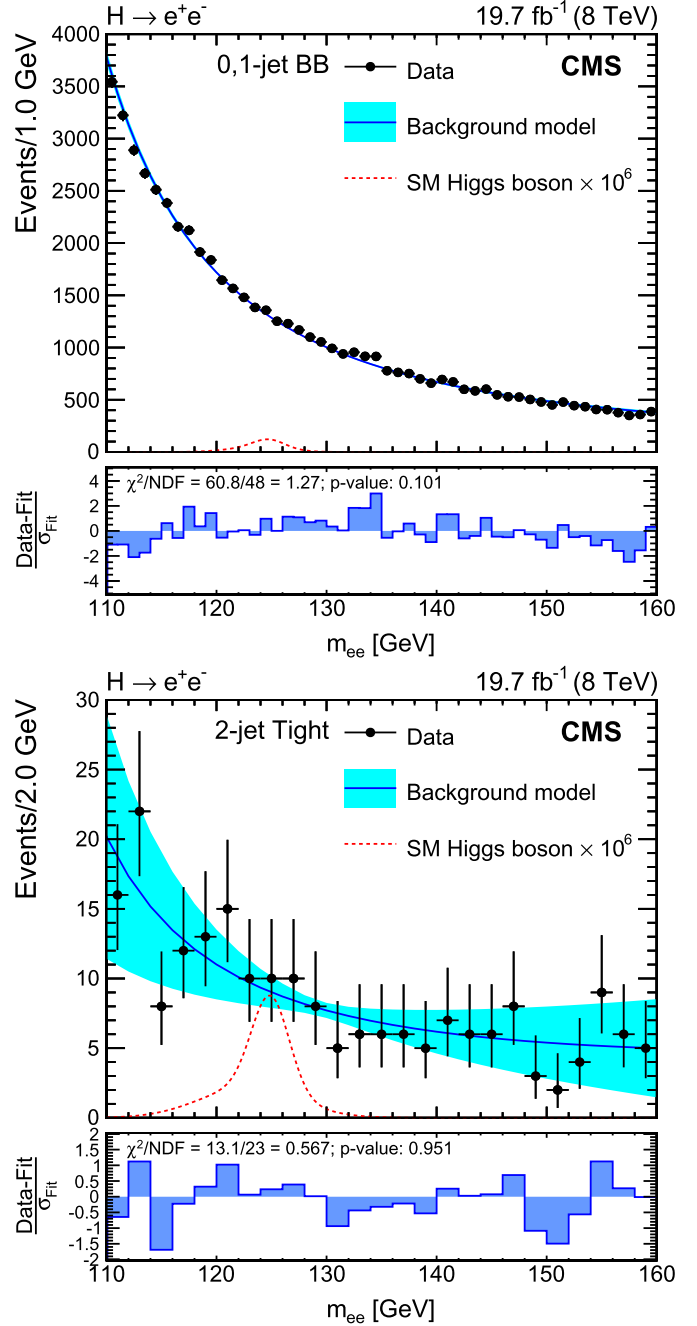


Fig. 4. The dielectron invariant mass at 8 TeV and the background model are shown for the 0,1-jet BB (top) and 2-jet Tight (bottom) categories. A best fit of the background model (see Section 6) is shown by a solid line, while its fit uncertainty is represented by a lighter band. The dotted line illustrates the expected SM Higgs boson signal enhanced by a factor of 10^6 , for $m_H = 125$ GeV. The lower histograms show the residual for each bin (Data-Fit) normalized by the Poisson statistical uncertainty of the background model (σ_{fit}). Also given are the sum of squares of the normalized residuals (χ^2) divided by the number of degrees of freedom (NDF) and the corresponding p -value assuming the sum follows the χ^2 distribution.

duction. Misidentified electrons make up a reducible background that is highly suppressed by the electron identification criteria. The reducible $H \rightarrow \gamma\gamma$ background is estimated from simulation to be negligible compared to other backgrounds, although large compared to the SM $H \rightarrow e^+e^-$ signal. The overall background shape and normalization are estimated by fitting the observed m_{ee} spectrum in data, assuming a smooth functional form, while the signal acceptance times selection efficiency is estimated from simulation.

Table 4

Details regarding each category of the $H \rightarrow e^+e^-$ analysis, for $19.7 \pm 0.5 \text{ fb}^{-1}$ at 8 TeV. Each row lists the category name, FWHM of the signal peak, acceptance times selection efficiency ($A\epsilon$) for GF, $A\epsilon$ for VBF, expected number of SM signal events in the category times 10^5 for $m_H = 125 \text{ GeV}$ (N_S), number of background events within an FWHM-wide window centered on 125 GeV estimated by a signal plus background fit to the data (N_B), number of observed events within an FWHM-wide window centered on 125 GeV (N_{Data}), systematic uncertainty to account for the parameterization of the background (N_P), and N_P divided by the statistical uncertainty on the fitted number of signal events (N_P/σ_{Stat}). The expected number of SM signal events is $N_S = \mathcal{L} \times (\sigma B A\epsilon)_{\text{GF}} + \mathcal{L} \times (\sigma B A\epsilon)_{\text{VBF}}$, where \mathcal{L} is the integrated luminosity and σB is the SM cross section times branching fraction.

Category	FWHM [GeV]	$A\epsilon$ [%]		$N_S \times 10^5$	N_B	N_{Data}	N_P	N_P/σ_{Stat} [%]
		GF	VBF					
0, 1-jet BB	4.0	27.5	16.7	56.1	5208.9	5163	75.0	61
0, 1-jet Not BB	7.1	17.0	9.7	34.6	8675.0	8748	308.7	174
2-jet Tight	3.8	0.5	10.7	2.6	17.7	22	19.5	71
2-jet Loose	4.7	1.0	7.3	3.1	79.5	84	43.2	88
Sum of categories	–	46.0	44.4	96.4	13981.1	14017	–	–

The analysis is performed only on proton–proton collision data collected at 8 TeV, corresponding to an integrated luminosity of $19.7 \pm 0.5 \text{ fb}^{-1}$.

The trigger selection requires two electrons, one with transverse energy, E_T , greater than 17 GeV and the other with E_T greater than 8 GeV. These electrons are required to be isolated with respect to additional energy deposits in the ECAL, and to pass selections on the ECAL cluster shape. In the offline selection, electrons are required to be inside the ECAL fiducial region: $|\eta| < 1.44$ (barrel) or $1.57 < |\eta| < 2.5$ (endcaps). Their energy is estimated by the same multivariate regression technique used in the CMS $H \rightarrow ZZ$ analysis [55], and their E_T is required to be greater than 25 GeV. Electrons are also required to satisfy standard CMS identification and isolation requirements, which correspond to a single electron efficiency of around 90% in the barrel and 80% in the endcaps [56].

To improve the sensitivity of the search we separate the sample into four distinct categories: two 0, 1-jet categories and two for which a pair of jets is required. The two 2-jet categories are designed to select events produced via the VBF process. The two jets are required to have an invariant mass greater than 500 (250) GeV for the 2-jet Tight (Loose) category, $p_T > 30$ (20) GeV, $|\Delta\eta(\text{jj})| > 3.0$, $|\Delta\phi(\text{jj}, e^+e^-)| > 2.6$, and $|z| = |\eta(e^+e^-) - [\eta(j_1) + \eta(j_2)]/2| < 2.5$ [57]. The cut on z ensures that the dielectron is produced centrally in the dijet reference frame, which helps to enhance the VBF signal over the Drell–Yan background. More details on the selection can be found in Ref. [58]. The rest of the events are classified into two 0, 1-jet categories. To exploit the better energy resolution of electrons in the barrel region, these categories are defined as: both electrons in the ECAL barrel (0, 1-jet BB) or at least one of them in the endcap (0, 1-jet Not BB). For each category, the FWHM of the expected signal peak, expected number of SM signal events for $m_H = 125 \text{ GeV}$, acceptance times selection efficiency, number of background events near 125 GeV, and number of data events near 125 GeV are shown in Table 4.

Data have been compared to the simulated Drell–Yan and $t\bar{t}$ background samples described in Section 4. In all categories, the dielectron invariant mass spectra from 110 to 160 GeV agree well, and the normalizations agree within 4.5%. Using simulation, the reducible background of $H \rightarrow \gamma\gamma$ events has also been estimated. For $m_H = 125 \text{ GeV}$, 0.23 SM $H \rightarrow \gamma\gamma$ events are expected to pass the dielectron selection compared to about 10^{-3} events for the SM $H \rightarrow e^+e^-$ signal. While this background is much larger than the SM $H \rightarrow e^+e^-$ signal, it is negligible compared to the Drell–Yan and $t\bar{t}$ backgrounds in each category.

Results are extracted from the data for m_H values between 120 and 150 GeV by fitting the mass spectra of the four categories in the range $110 < m_{ee} < 160 \text{ GeV}$. The parameterizations used for the signal and background are the same as used in the $\mu^+\mu^-$ search, a double-Gaussian function and Eq. (1), respec-

tively. Background-only m_{ee} fits to data are shown in Fig. 4 for the 0, 1-jet BB and 2-jet Tight categories.

Systematic uncertainties are estimated and incorporated into the results using the same methods as in the $\mu^+\mu^-$ search (see Section 5). Table 3 lists the systematic uncertainties in the signal yield. The pileup modeling, pileup jet rejection, and MC statistics systematic uncertainties are small and neglected for the e^+e^- search. The systematic uncertainties due to the jet energy resolution and absolute jet energy scale are combined and listed as “jet energy scale” in Table 3. The uncertainty related to the choice of background parameterization in terms of the number of signal events (N_P) is shown in Table 4. This systematic uncertainty is larger than all of the others, and removing it would lower the expected limit by 28%, for $m_H = 125 \text{ GeV}$.

No significant excess of events is observed. Upper limits on $\sigma(8 \text{ TeV})B$ and B are reported. The observed 95% CL upper limit on $\sigma(8 \text{ TeV})B$ at 125 GeV is 0.041 pb while the background-only expected limit is $0.052^{+0.022}_{-0.015}$ pb. Assuming the SM production cross section, this corresponds to an observed upper limit on $B(H \rightarrow e^+e^-)$ of 0.0019, which is approximately 3.7×10^5 times the SM prediction. Upper limits on $\sigma(8 \text{ TeV})B$ are shown for Higgs boson masses from 120 to 150 GeV at the 95% CL in Fig. 3 (bottom).

8. Summary

Results are presented from a search for an SM-like Higgs boson decaying to $\mu^+\mu^-$ and for the first time to e^+e^- . For the search in $\mu^+\mu^-$, the analyzed CMS data correspond to integrated luminosities of $5.0 \pm 0.1 \text{ fb}^{-1}$ collected at 7 TeV and $19.7 \pm 0.5 \text{ fb}^{-1}$ collected at 8 TeV, while only the 8 TeV data are used for the search in the e^+e^- channel. The Higgs boson signal is sought as a narrow peak in the dilepton invariant mass spectrum on top of a smoothly falling background dominated by the Drell–Yan, $t\bar{t}$, and vector boson pair-production processes. Events are split into categories corresponding to different production topologies and dilepton invariant mass resolutions. The signal strength is then extracted using a simultaneous fit to the dilepton invariant mass spectra in all of the categories.

No significant $H \rightarrow \mu^+\mu^-$ signal is observed. Upper limits are set on the signal strength at the 95% CL. Results are presented for Higgs boson masses between 120 and 150 GeV. The combined observed limit on the signal strength, for a Higgs boson with a mass of 125 GeV, is 7.4, while the expected limit is $6.5^{+2.8}_{-1.9}$. Assuming the SM production cross section, this corresponds to an upper limit of 0.0016 on $B(H \rightarrow \mu^+\mu^-)$. For a Higgs boson mass of 125 GeV, the best fit signal strength is $0.8^{+3.5}_{-3.4}$.

In the $H \rightarrow e^+e^-$ channel, SM Higgs boson decays are far too rare to detect, and no signal is observed. For a Higgs boson mass of 125 GeV, a 95% CL upper limit of 0.041 pb is set on $\sigma B(H \rightarrow e^+e^-)$ at 8 TeV. Assuming the SM production cross section, this

corresponds to an upper limit on $\mathcal{B}(H \rightarrow e^+e^-)$ of 0.0019, which is approximately 3.7×10^5 times the SM prediction. For comparison, the $H \rightarrow \mu^+\mu^-$ observed 95% CL upper limit on $\sigma\mathcal{B}(H \rightarrow \mu^+\mu^-)$ is 0.033 pb (using only 8 TeV data), which is 7.0 times the expected SM Higgs boson cross section.

These results, together with recent evidence for the 125 GeV boson's coupling to τ -leptons [6] with a larger \mathcal{B} consistent with the SM value of 0.0632 ± 0.0036 [5], confirm the SM prediction that the leptonic couplings of the new boson are not flavour-universal.

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CMS Collaboration

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan¹, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, D. Rabady², B. Rahbaran, H. Rohringer, R. Schöffbeck, J. Strauss, A. Taurok, W. Treberer-Treberspur, W. Waltenberger, C.-E. Wulz¹

Institut für Hochenergiephysik der OeAW, Wien, Austria

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

National Centre for Particle and High Energy Physics, Minsk, Belarus

S. Alderweireldt, M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, S. Luyckx, S. Ochesanu, R. Rougny, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, N. Daci, N. Heracleous, J. Keaveney, S. Lowette, M. Maes, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Vrije Universiteit Brussel, Brussel, Belgium

C. Caillol, B. Clerbaux, G. De Lentdecker, D. Dobur, L. Favart, A.P.R. Gay, A. Grebenyuk, A. Léonard, A. Mohammadi, L. Perniè², T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang, F. Zenoni

Université Libre de Bruxelles, Bruxelles, Belgium

V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Crucy, S. Dildick, A. Fagot, G. Garcia, J. McCartin, A.A. Ocampo Rios, D. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, C. Beluffi³, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco⁴, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, C. Nuttens, D. Pagano, L. Perrini, A. Pin, K. Piotrkowski, A. Popov⁵, L. Quertenmont, M. Selvaggi, M. Vidal Marono, J.M. Vizan Garcia

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Université de Mons, Mons, Belgium

W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, T. Dos Reis Martins, C. Mora Herrera, M.E. Pol

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

W. Carvalho, J. Chinellato⁶, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote⁶, A. Vilela Pereira

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

C.A. Bernardes^b, S. Dogra^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a

^a *Universidade Estadual Paulista, São Paulo, Brazil*

^b *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, V. Genchev², P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, R. Du, C.H. Jiang, R. Plestina⁷, F. Romeo, J. Tao, Z. Wang

Institute of High Energy Physics, Beijing, China

C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, W. Zou

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

C. Avila, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, D. Polic, I. Puljak

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, L. Sudic

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

University of Cyprus, Nicosia, Cyprus

M. Bodlak, M. Finger, M. Finger Jr.⁸

Charles University, Prague, Czech Republic

Y. Assran⁹, A. Ellithi Kamel¹⁰, M.A. Mahmoud¹¹, A. Radi^{12,13}

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

M. Kadastik, M. Murumaa, M. Raidal, A. Tiko

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, G. Fedi, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M. Titov

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

S. Baffioni, F. Beaudette, P. Busson, C. Charlot, T. Dahms, M. Dalchenko, L. Dobrzynski, N. Filipovic, A. Florent, R. Granier de Cassagnac, L. Mastrolorenzo, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, C. Veelken, Y. Yilmaz, A. Zabi

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France

J.-L. Agram¹⁴, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte¹⁴, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, P. Van Hove

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

S. Gadrat

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France

S. Beauceron, N. Beaupere, G. Boudoul², E. Bouvier, S. Brochet, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo², P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

Z. Tsamalaidze⁸

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, M. Bontenackels, M. Edelhoff, L. Feld, O. Hindrichs, K. Klein, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, H. Weber, B. Wittmer, V. Zhukov⁵

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, M. Olschewski, K. Padeken, P. Papacz, H. Reithler, S.A. Schmitz, L. Sonnenschein, D. Teyssier, S. Thüer, M. Weber

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, A. Heister, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Künsken, J. Lingemann², A. Nowack, I.M. Nugent, L. Perchalla, O. Pooth, A. Stahl

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

I. Asin, N. Bartosik, J. Behr, W. Behrenhoff, U. Behrens, A.J. Bell, M. Bergholz¹⁵, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, J. Garay Garcia, A. Geiser, P. Gunnellini, J. Hauk, M. Hempel¹⁵, D. Horton, H. Jung, A. Kalogeropoulos, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, D. Krücker, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁵, B. Lutz, R. Mankel, I. Marfin¹⁵, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, O. Novgorodova, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, B. Roland, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, R. Schmidt¹⁵, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, A.D.R. Vargas Trevino, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, H. Kirschenmann, R. Klanner, R. Kogler, J. Lange, T. Lapsien, T. Lenz, I. Marchesini, J. Ott, T. Peiffer, N. Pietsch, J. Poehlsen, T. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, D. Troendle, E. Usai, L. Vanelderden, A. Vanhoefer

University of Hamburg, Hamburg, Germany

C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Frensch, M. Giffels, F. Hartmann², T. Hauth², U. Husemann, I. Katkov⁵, A. Kornmayer², E. Kuznetsova, P. Lobelle Pardo, M.U. Mozer, Th. Müller, A. Nürnberg, G. Quast, K. Rabbertz, F. Ratnikov, S. Röcker, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, T. Gerasis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Markou, C. Markou, A. Psallidas, I. Topsis-Giotis

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Stiliaris

University of Athens, Athens, Greece

X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, P. Hidas, D. Horvath¹⁶, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁷, A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi¹⁸, J. Molnar, J. Palinkas, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi, B. Ujvari

University of Debrecen, Debrecen, Hungary

S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

S.B. Beri, V. Bhatnagar, R. Gupta, U. Bhawandeep, A.K. Kalsi, M. Kaur, R. Kumar, M. Mittal, N. Nishu, J.B. Singh

Panjab University, Chandigarh, India

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty², L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik¹⁹, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu²⁰, G. Kole, S. Kumar, M. Maity¹⁹, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage²¹

Tata Institute of Fundamental Research, Mumbai, India

H. Bakhshiansohi, H. Behnamian, S.M. Etesami²², A. Fahim²³, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh²⁴, M. Zeinali

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, S. My^{a,c}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b,2}, G. Selvaggi^{a,b}, L. Silvestris^{a,2}, R. Venditti^{a,b}, G. Zito^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b},

T. Rovelli ^{a,b}, G.P. Siroli ^{a,b}, N. Tosi ^{a,b}, R. Travaglini ^{a,b}

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo ^{a,b}, G. Cappello ^a, M. Chiorboli ^{a,b}, S. Costa ^{a,b}, F. Giordano ^{a,2}, R. Potenza ^{a,b}, A. Tricomi ^{a,b}, C. Tuve ^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli ^a, V. Ciulli ^{a,b}, C. Civinini ^a, R. D'Alessandro ^{a,b}, E. Focardi ^{a,b}, E. Gallo ^a, S. Gonzi ^{a,b}, V. Gori ^{a,b,2}, P. Lenzi ^{a,b}, M. Meschini ^a, S. Paoletti ^a, G. Sguazzoni ^a, A. Tropicano ^{a,b}

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

R. Ferretti ^{a,b}, F. Ferro ^a, M. Lo Vetere ^{a,b}, E. Robutti ^a, S. Tosi ^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

M.E. Dinardo ^{a,b}, S. Fiorendi ^{a,b}, S. Gennai ^{a,2}, R. Gerosa ^{a,b,2}, A. Ghezzi ^{a,b}, P. Govoni ^{a,b}, M.T. Lucchini ^{a,b,2}, S. Malvezzi ^a, R.A. Manzoni ^{a,b}, A. Martelli ^{a,b}, B. Marzocchi ^{a,b,2}, D. Menasce ^a, L. Moroni ^a, M. Paganoni ^{a,b}, D. Pedrini ^a, S. Ragazzi ^{a,b}, N. Redaelli ^a, T. Tabarelli de Fatis ^{a,b}

^a INFN Sezione di Milano-Bicocca, Milano, Italy

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo ^a, N. Cavallo ^{a,c}, S. Di Guida ^{a,d,2}, F. Fabozzi ^{a,c}, A.O.M. Iorio ^{a,b}, L. Lista ^a, S. Meola ^{a,d,2}, M. Merola ^a, P. Paolucci ^{a,2}

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli 'Federico II', Napoli, Italy

^c Università della Basilicata (Potenza), Napoli, Italy

^d Università G. Marconi (Roma), Napoli, Italy

P. Azzi ^a, N. Bacchetta ^a, D. Bisello ^{a,b}, A. Branca ^{a,b}, R. Carlin ^{a,b}, P. Checchia ^a, M. Dall'Osso ^{a,b}, T. Dorigo ^a, U. Dosselli ^a, M. Galanti ^{a,b}, F. Gasparini ^{a,b}, U. Gasparini ^{a,b}, P. Giubilato ^{a,b}, A. Gozzelino ^a, K. Kanishchev ^{a,c}, S. Lacaprara ^a, M. Margoni ^{a,b}, A.T. Meneguzzo ^{a,b}, J. Pazzini ^{a,b}, N. Pozzobon ^{a,b}, P. Ronchese ^{a,b}, F. Simonetto ^{a,b}, E. Torassa ^a, M. Tosi ^{a,b}, P. Zotto ^{a,b}, A. Zucchetta ^{a,b}, G. Zumerle ^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento (Trento), Padova, Italy

M. Gabusi ^{a,b}, S.P. Ratti ^{a,b}, V. Re ^a, C. Riccardi ^{a,b}, P. Salvini ^a, P. Vitulo ^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

M. Biasini ^{a,b}, G.M. Bilei ^a, D. Ciangottini ^{a,b}, L. Fanò ^{a,b}, P. Lariccia ^{a,b}, G. Mantovani ^{a,b}, M. Menichelli ^a, A. Saha ^a, A. Santocchia ^{a,b}, A. Spiezia ^{a,b,2}

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

K. Androsova ^{a,25}, P. Azzurri ^a, G. Bagliesi ^a, J. Bernardini ^a, T. Boccali ^a, G. Broccolo ^{a,c}, R. Castaldi ^a, M.A. Ciocci ^{a,25}, R. Dell'Orso ^a, S. Donato ^{a,c}, F. Fiori ^{a,c}, L. Foà ^{a,c}, A. Giassi ^a, M.T. Grippo ^{a,25}, F. Ligabue ^{a,c}, T. Lomtadze ^a, L. Martini ^{a,b}, A. Messineo ^{a,b}, C.S. Moon ^{a,26}, F. Palla ^{a,2}, A. Rizzi ^{a,b}, A. Savoy-Navarro ^{a,27},

A.T. Serban^a, P. Spagnolo^a, P. Squillacioti^{a,25}, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verдини^a, C. Vernieri^{a,c,2}

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone^{a,b}, F. Cavallari^a, G. D'imperio^{a,b}, D. Del Re^{a,b}, M. Diemoz^a, M. Grassi^{a,b}, C. Jorda^a, E. Longo^{a,b}, F. Margaroli^{a,b}, P. Meridiani^a, F. Micheli^{a,b,2}, S. Nourbakhsh^{a,b}, G. Organtini^{a,b}, R. Paramatti^a, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}, L. Soffi^{a,b,2}, P. Traczyk^{a,b}

^a INFN Sezione di Roma, Roma, Italy

^b Università di Roma, Roma, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b,2}, M. Arneodo^{a,c}, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, S. Casasso^{a,b,2}, M. Costa^{a,b}, A. Degano^{a,b}, N. Demaria^a, L. Finco^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, M. Musich^a, M.M. Obertino^{a,c,2}, G. Ortona^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, A. Potenza^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, A. Solano^{a,b}, A. Staiano^a, U. Tamponi^a

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale (Novara), Torino, Italy

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, C. La Licata^{a,b}, M. Marone^{a,b}, A. Schizzi^{a,b}, T. Umer^{a,b}, A. Zanetti^a

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

S. Chang, A. Kropivnitskaya, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, A. Sakharov, D.C. Son

Kyungpook National University, Daegu, Republic of Korea

T.J. Kim

Chonbuk National University, Jeonju, Republic of Korea

J.Y. Kim, S. Song

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K.S. Lee, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

M. Choi, J.H. Kim, I.C. Park, G. Ryu, M.S. Ryu

University of Seoul, Seoul, Republic of Korea

Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, H. Seo, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

A. Juodagalvis

Vilnius University, Vilnius, Lithuania

J.R. Komaragiri, M.A.B. Md Ali

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz²⁸, A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

I. Pedraza, H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

E. Casimiro Linares, A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler, S. Reucroft

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, M.A. Shah, M. Shoaib

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, W. Wolszczak

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

P. Bargassa, C. Beirão Da Cruz E Silva, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, J. Varela, P. Vischia

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

P. Bunin, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev²⁹, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim³⁰, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin³¹, L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, M. Perfilov, S. Petrushanko, V. Savrin

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

P. Adzic³², M. Ekmedzic, J. Milosevic, V. Rekovic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

J. Alcaraz Maestre, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad Autónoma de Madrid, Madrid, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, C. Bernet⁷, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi³³, M. D'Alfonso, D. d'Enterria, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, J. Marrouche, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, P. Musella, L. Orsini, L. Pape, E. Perez, L. Perrozzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, M. Plagge, A. Racz, G. Rolandi³⁴, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁵, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsiros, G.I. Veres¹⁷, N. Wardle, H.K. Wöhri, H. Wollny, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Băni, L. Bianchini, M.A. Buchmann, B. Casal, N. Chanon, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, D. Hits, J. Hoss, W. Lusterhmann, B. Mangano, A.C. Marini, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, N. Mohr, C. Nägeli³⁶, F. Nessi-Tedaldi, F. Pandolfi, F. Pauss, M. Peruzzi, M. Quittnat, L. Rebane, M. Rossini, A. Starodumov³⁷, M. Takahashi, K. Theofilatos, R. Wallny, H.A. Weber

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

C. Amsler³⁸, M.F. Canelli, V. Chiochia, A. De Cosa, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, B. Millan Mejias, J. Ngadiuba, P. Robmann, F.J. Ronga, S. Taroni, M. Verzetti, Y. Yang

Universität Zürich, Zurich, Switzerland

M. Cardaci, K.H. Chen, C. Ferro, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, U. Grundler, W.-S. Hou, K.Y. Kao, Y.J. Lei, Y.F. Liu, R.-S. Lu, D. Majumder, E. Petrakou, Y.M. Tzeng, R. Wilken

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

A. Adiguzel, M.N. Bakirci³⁹, S. Cerci⁴⁰, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut⁴¹, K. Ozdemir, S. Ozturk³⁹, A. Polatoz, D. Sunar Cerci⁴⁰, B. Tali⁴⁰, H. Topakli³⁹, M. Vergili

Cukurova University, Adana, Turkey

I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan⁴², G. Karapinar⁴³, K. Ocalan⁴⁴, S. Sekmen, U.E. Surat, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, B. Isildak⁴⁵, M. Kaya⁴⁶, O. Kaya⁴⁷

Bogazici University, Istanbul, Turkey

K. Cankocak, F.I. Vardarli

Istanbul Technical University, Istanbul, Turkey

L. Levchuk, P. Sorokin

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold⁴⁸, S. Paramesvaran, A. Poll, S. Senkin, V.J. Smith, T. Williams

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev⁴⁹, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, W.J. Womersley, S.D. Worm

Rutherford Appleton Laboratory, Didcot, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, P. Dunne, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, G. Hall, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas⁴⁸, L. Lyons, A.-M. Magnan, S. Malik, B. Mathias,

J. Nash, A. Nikitenko³⁷, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp[†], A. Tapper, M. Vazquez Acosta, T. Virdee, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, T. Scarborough

Baylor University, Waco, USA

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

A. Avetisyan, T. Bose, C. Fantasia, P. Lawson, C. Richardson, J. Rohlf, J. St. John, L. Sulak

Boston University, Boston, USA

J. Alimena, E. Berry, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, N. Dhingra, A. Ferapontov, A. Garabedian, U. Heintz, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, M. Segala, T. Sinthuprasith, T. Speer, J. Swanson

Brown University, Providence, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, T. Miceli, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, M. Searle, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Davis, Davis, USA

R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, G. Rakness, E. Takasugi, V. Valuev, M. Weber

University of California, Los Angeles, USA

K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Iova Rikova, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, A. Luthra, M. Malberti, H. Nguyen, M. Olmedo Negrete, A. Shrinivas, S. Sumowidagdo, S. Wimpenny

University of California, Riverside, Riverside, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, D. Evans, A. Holzner, R. Kelley, D. Klein, D. Kovalskyi, M. Lebourgeois, J. Letts, I. Macneill, D. Olivito, S. Padhi, C. Palmer, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, Y. Tu, A. Vartak, C. Welke, F. Würthwein, A. Yagil

University of California, San Diego, La Jolla, USA

D. Barge, J. Bradmiller-Feld, C. Campagnari, T. Danielson, A. Dishaw, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Incandela, C. Justus, N. Mccoll, J. Richman, D. Stuart, W. To, C. West, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, C. Rogan, M. Spiropulu, V. Timciuc, J.R. Vlimant, R. Wilkinson, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, USA

V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, Y. Iiyama, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, A. Gaz, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado at Boulder, Boulder, USA

J. Alexander, A. Chatterjee, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, L. Skinnari, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, L. Winstrom, P. Wittich

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, K. Kaadze, B. Klima, B. Kreis, S. Kwan, J. Linacre, D. Lincoln, R. Lipton, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, Y. Musienko²⁹, S. Nahn, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, A. Whitbeck, J. Whitmore, F. Yang

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, M. Carver, T. Cheng, D. Curry, S. Das, M. De Gruttola, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic⁵⁰, G. Mitselmakher, L. Muniz, A. Rinkevicius, L. Shchutska, M. Snowball, D. Sperka, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida State University, Tallahassee, USA

M.M. Baarmand, M. Hohlmann, H. Kalakhety, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, V.E. Bazterra, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, P. Kurt, D.H. Moon, C. O'Brien, C. Silkworth, P. Turner, N. Varelas

University of Illinois at Chicago (UIC), Chicago, USA

E.A. Albayrak⁵¹, B. Bilki⁵², W. Clarida, K. Dilsiz, F. Duru, M. Haytmyradov, J.-P. Merlo, H. Mermerkaya⁵³, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁵¹, A. Penzo, R. Rahmat, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin⁵⁴, K. Yi

The University of Iowa, Iowa City, USA

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, A.V. Gritsan, P. Maksimovic, C. Martin, M. Swartz

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, G. Benelli, C. Bruner, R.P. Kenny III, M. Malek, M. Murray, D. Noonan, S. Sanders, J. Sekaric, R. Stringer, Q. Wang, J.S. Wood

The University of Kansas, Lawrence, USA

A.F. Barfuss, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, S. Shrestha, N. Skhirtladze, I. Svintradze

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, A. Belloni, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Skuja, M.B. Tonjes, S.C. Tonwar

University of Maryland, College Park, USA

A. Apyan, R. Barbieri, G. Bauer, W. Busza, I.A. Cali, M. Chan, L. Di Matteo, V. Dutta, G. Gomez Ceballos, M. Goncharov, D. Gulhan, M. Klute, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, T. Ma, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, F. Stöckli, K. Sumorok, D. Velicanu, J. Veverka, B. Wyslouch, M. Yang, M. Zanetti, V. Zhukova

Massachusetts Institute of Technology, Cambridge, USA

B. Dahmes, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, A. Singovsky, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, R. Gonzalez Suarez, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, S. Malik, F. Meier, G.R. Snow, M. Zvada

University of Nebraska-Lincoln, Lincoln, USA

J. Dolen, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, S. Rappoccio

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, D. Trocino, R.-J. Wang, D. Wood, J. Zhang

Northeastern University, Boston, USA

K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Velasco, S. Won

Northwestern University, Evanston, USA

A. Brinkerhoff, K.M. Chan, A. Drozdetskiy, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Luo, S. Lynch, N. Marinelli, T. Pearson, M. Planer, R. Ruchti, N. Valls, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, G. Smith, B.L. Winer, H. Wolfe, H.W. Wulsin

The Ohio State University, Columbus, USA

O. Driga, P. Elmer, P. Hebda, A. Hunt, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland², C. Tully, J.S. Werner, A. Zuranski

Princeton University, Princeton, USA

E. Brownson, H. Mendez, J.E. Ramirez Vargas

University of Puerto Rico, Mayaguez, USA

V.E. Barnes, D. Benedetti, D. Bortoletto, M. De Mattia, L. Gutay, Z. Hu, M.K. Jha, M. Jones, K. Jung, M. Kress, N. Leonardo, D. Lopes Pegna, V. Maroussov, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University, West Lafayette, USA

N. Parashar, J. Stupak

Purdue University Calumet, Hammond, USA

A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B. Michlin, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, A. Khukhunaishvili, G. Petrillo, D. Vishnevskiy

University of Rochester, Rochester, USA

R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, C. Mesropian

The Rockefeller University, New York, USA

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, S. Kaplan, A. Lath, S. Panwalkar, M. Park, R. Patel, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

Rutgers, The State University of New Jersey, Piscataway, USA

K. Rose, S. Spanier, A. York

University of Tennessee, Knoxville, USA

O. Bouhali⁵⁵, A. Castaneda Hernandez, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁶, V. Khotilovich, V. Krutelyov, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Rose, A. Safonov, T. Sakuma, I. Suarez, A. Tatarinov

Texas A&M University, College Station, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, K. Kovitanggoon, S. Kunori, S.W. Lee, T. Libeiro, I. Volobouev

Texas Tech University, Lubbock, USA

E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, W. Johns, C. Maguire, Y. Mao, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

Vanderbilt University, Nashville, USA

M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, J. Wood

University of Virginia, Charlottesville, USA

C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

Wayne State University, Detroit, USA

D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, E. Friis, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, C. Lazaridis, A. Levine, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Sarangi, A. Savin, W.H. Smith, D. Taylor, P. Verwilligen, C. Vuosalo, N. Woods

University of Wisconsin, Madison, USA

[†] Deceased.

¹ Also at Vienna University of Technology, Vienna, Austria.

² Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

³ Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.

⁴ Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.

⁵ Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

⁶ Also at Universidade Estadual de Campinas, Campinas, Brazil.

⁷ Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.

⁸ Also at Joint Institute for Nuclear Research, Dubna, Russia.

⁹ Also at Suez University, Suez, Egypt.

¹⁰ Also at Cairo University, Cairo, Egypt.

¹¹ Also at Fayoum University, El-Fayoum, Egypt.

¹² Also at British University in Egypt, Cairo, Egypt.

¹³ Now at Sultan Qaboos University, Muscat, Oman.

¹⁴ Also at Université de Haute Alsace, Mulhouse, France.

¹⁵ Also at Brandenburg University of Technology, Cottbus, Germany.

¹⁶ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

¹⁷ Also at Eötvös Loránd University, Budapest, Hungary.

¹⁸ Also at University of Debrecen, Debrecen, Hungary.

¹⁹ Also at University of Visva-Bharati, Santiniketan, India.

²⁰ Now at King Abdulaziz University, Jeddah, Saudi Arabia.

²¹ Also at University of Ruhuna, Matara, Sri Lanka.

²² Also at Isfahan University of Technology, Isfahan, Iran.

²³ Also at Sharif University of Technology, Tehran, Iran.

²⁴ Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

²⁵ Also at Università degli Studi di Siena, Siena, Italy.

²⁶ Also at Centre National de la Recherche Scientifique (CNRS)–IN2P3, Paris, France.

²⁷ Also at Purdue University, West Lafayette, USA.

²⁸ Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico.

²⁹ Also at Institute for Nuclear Research, Moscow, Russia.

³⁰ Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

³¹ Also at California Institute of Technology, Pasadena, USA.

³² Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.

³³ Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.

³⁴ Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.

³⁵ Also at University of Athens, Athens, Greece.

³⁶ Also at Paul Scherrer Institut, Villigen, Switzerland.

³⁷ Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

³⁸ Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.

³⁹ Also at Gaziosmanpasa University, Tokat, Turkey.

⁴⁰ Also at Adiyaman University, Adiyaman, Turkey.

⁴¹ Also at Cag University, Mersin, Turkey.

⁴² Also at Anadolu University, Eskisehir, Turkey.

⁴³ Also at Izmir Institute of Technology, Izmir, Turkey.

⁴⁴ Also at Necmettin Erbakan University, Konya, Turkey.

⁴⁵ Also at Ozyegin University, Istanbul, Turkey.

⁴⁶ Also at Marmara University, Istanbul, Turkey.

⁴⁷ Also at Kafkas University, Kars, Turkey.

⁴⁸ Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.

⁴⁹ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

⁵⁰ Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

⁵¹ Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

⁵² Also at Argonne National Laboratory, Argonne, USA.

⁵³ Also at Erzincan University, Erzincan, Turkey.

⁵⁴ Also at Yildiz Technical University, Istanbul, Turkey.

⁵⁵ Also at Texas A&M University at Qatar, Doha, Qatar.

⁵⁶ Also at Kyungpook National University, Daegu, Korea.